Received: 5 June 2017 | Accepted: 6 June 2017
DOI: 10.1002/hyp.11253

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INVITED COMMENTARY

A role for meta-analysis in hydrology

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1 | INTRODUCTION

Research in hydrology has evolved from a rich history of site-based (usually catchment-based) field data collection. These studies typically have a small sample size—that is, one study hillslope or catchment and usually no replication. Although different to many other scientific fields where replication is sacrosanct, such field-based discovery science has driven much of what we know about infiltration, run-off processes, and ecohydrological dynamics. But although field work at single sites continues to unearth new forms of hydrological behaviour—and this is much needed to understand better "how catchments work"—process inference by one-off field experiments has significant limitations. Although some of these limitations can be mediated by replication and stronger adherence to the scientific method and formal hypothesis testing (Hooper, 2001; Pfister & Kirchner, 2017), many limitations remain.

One tool that has not yet been fully exploited in hydrology is meta-analysis. We are certainly not the first to advocate for meta-analysis in hydrology, and we note important previous work in large-scale erosion and sediment delivery (Corbel, 1964; Milliman & Syvitski, 1992) and forest hydrology (Farley, Jobbagy, & Jackson, 2005). Nevertheless, uptake has been limited generally. Much more common is the traditional "review paper" where an author identifies studies on a particular topic, summarizes their findings, and reports a conclusion in narrative form. But while useful, reviews lack transparency and are subjective (Borenstein, Hedges, Higgins, & Rothstein, 2010). This is something of a double whammy in a field such as hydrology where the field studies often reviewed are themselves one-off and exploratory in nature! Consequently, a review paper author may assign implicitly more weight or credence to one study over another based on criteria that are not always articulated. Although such narrative reviews do serve a useful role as a stock-taking for the state-of-knowledge about a particular research question (with many recent examples[1]), they are not objective and they are not quantitative.

[1] Recent reviews summarizing hydrological responses to forest change (M. Zhang et al., 2017), distributed temperature sensing applications in hydrogeology (Bense et al., 2016), and hydrological modelling of urbanized catchments (Salvadore, Bronders, & Batelaan, 2015).

Meta-analyses are a different type of review methodology, which involve a clear set of criteria used in the literature search process. Meta-analyses provide an objective measure of which studies are to be included in or excluded from the analysis. And they use appropriate statistical techniques to integrate and summarize the results of these studies.

This commentary explores the role for meta-analysis in hydrology. We consolidate the heretofore dispersed interests in the technique by briefly describing the meta-analysis methodology and then outlining a vision for its use in process hydrology questions to complement current field activities. We argue that meta-analysis could be a powerful complement to field studies by aiding retrospective synthesis of published research whereby divergent results on the same research question are apparent. More importantly, in a field such as hydrology where the primary literature often has limited statistical power and where researchers can [dangerously] make claims that are deemed true but are likely to be false, large studies or low-bias meta-analysis may prove helpful (Ioannidis, 2005).

2 | META-ANALYSIS AS RETROSPECTIVE SYNTHESIS

Review papers generally take the form of a narrative review. The process in writing a narrative review is simple: identify and read the studies about a particular topic, summarize the findings, and report a conclusion in narrative form.

Systematic reviews are another type of review methodology, which involve a clear set of criteria used in the literature search process. This provides an objective measure for which studies are to be included in or excluded from the analysis. When appropriate statistical techniques are employed in integrating and summarizing the results of these studies, the systematic review becomes a meta-analysis.

Figure 1 shows that out of 2,973 published manuscripts in hydrology (using the string "hydrolog*" OR "hydrology" in title, abstract, or keyword and restricting the search to document type "review") since 1990, only 87 (c. 3%) may be classified as meta-analyses where

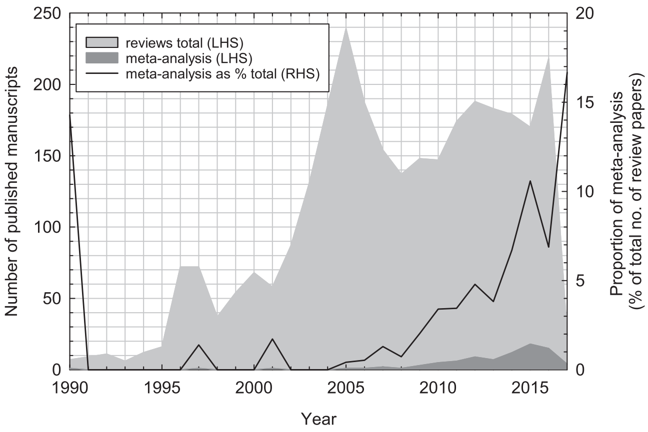

FIGURE 1 Review papers published from 1990 to the first quarter of 2017 matching Scopus queries. LHS (left-hand side): Studies that carry the tag "hydrolog*" OR "hydrology" in title, abstract, or keyword are total number of review papers (light grey area fill). Meta-analysis papers are represented by the dark grey area fill. RHS (right-hand side): Meta-analysis as a percentage of total number of review papers

weights (i.e., levels of importance) are assigned to each study based on a mathematical criterion.

Retrospective syntheses through meta-analysis provide the ability to consider a wide range of possibilities, states, and outcomes that is larger and more exhaustive than what could be possibly captured by a single primary study. Recent examples of retrospective synthesis meta-analyses include Zhuo, Dai, and Han (2015); Viglizzo, Nosetto, and Jobbágy, Ricard, Frank (2015); and Evaristo and McDonnell (2017). If we examine these three studies further, it is clear where and how meta-analysis can go beyond statements and contributions of the primary studies they include—and explore new questions, only possible with large "sample size" meta-analysis.

For instance, Zhuo et al. (2015) performed a meta-analysis of 119 flow models in 76 catchments to determine how to match catchment complexity with the flow modelling approach. Their meta-analysis found that semidistributed models were most suitable in large catchments (>3,000 km^2), irrespective of climate, soil type, and land cover. The utility of Zhuo et al.'s meta-analysis resides not in identifying which model type is suitable for a particular catchment (that has already been reported in primary studies) but in identifying which model type is most suitable for a given catchment complexity, represented by climate, soil type, land cover, and catchment scale.

Viglizzo et al. (2015) used meta-analysis to understand the drivers of ecosystem transitions, for example, grasslands to shrublands and forests to shrublands. They performed a meta-analysis of 685 studies in three climatic regions and three ecosystems. Their meta-analysis found that, contrary to some evidence asserting anthropogenic and biophysical disturbance controls (e.g., overgrazing, fire, and droughts) over ecosystem transitions, ecohydrological context drives such transitions at a hierarchical level higher than anthropogenic disturbance. The utility of Viglizzo et al.'s meta-analysis resides not in invalidating the site-specific claims (those have already been reported in primary studies) but in identifying the hierarchical controls over ecosystem transitions at the larger, aggregated scale of their meta-analysis.

Lastly, and most recently, Evaristo and McDonnell (2017) used meta-analysis to quantify the use of groundwater by vegetation. They showed that despite the substantial variability with respect to prevalence of groundwater use by vegetation in primary studies—from a low of 0.05% to a high of 99%, reflecting site- and species-level differences across studies—at the aggregated scale of their global meta-analysis, prevalence was around 37% with relatively modest dispersion (95% confidence interval, 28–46%). The utility of Evaristo and McDonnell's meta-analysis resides not in estimating the wide within-study variability (again, all that has already been reported in primary studies) but in providing an estimate of prevalence at the global scale and its associated dispersion, which places the prevalence estimate in a statistically robust context.

3 | META-ANALYSIS AND STATISTICAL POWER

The second utility of a meta-analysis in hydrological studies is for evaluating claims based on primary studies that, individually, have small statistical power. Backed by a compelling set of simulations, Ioannidis (2005) showed that the smaller the sample size of a study (i.e., smaller statistical power assuming similar effect size), the less likely the research findings are to be true.

One recent example topic in hydrology is ecohydrological separation, the phenomenological observation whereby plants use water of a character different from the mobile water found in soils, groundwater, and streams. The first to report and suggest ecohydrological separation was Brooks, Barnard, Coulombe, and McDonnell (2010) in a Mediterranean climate setting in Oregon, USA (xylem water sample size N = 88). This was followed by Goldsmith et al. (2012) in a seasonally dry tropical forest in Veracruz, Mexico (N = 57), and then by Evaristo, McDonnell, Scholl, Bruijnzeel, and Chun (2016) at two sites with less seasonality in Puerto Rico (N = 71). A subsequent meta-analysis of 47 studies (N = 1,460) by Evaristo, Jasechko, and McDonnell (2015) showed that ecohydrological separation was widespread, the rule rather than the exception. Notwithstanding, a study by Geris et al. (2015) did not observe ecohydrological separation in a "low-energy" site in Scotland. Despite the small sample size (N = 11) of Geris et al.'s study, it is often cited as a refutation of ecohydrological separation. Although the Scotland field study is indeed useful, it nevertheless holds less credence vis-à-vis ecohydrological separation because of its small statistical power (assuming similar effect size). This is an example of judgmental bias— asymmetric attention or disconfirmation bias (Nuzzo, 2015)—tacitly conveying primacy to a single study that shows lack of evidence for ecohydrological separation, when three prior field studies on the same research question and 37 additional studies show evidence of ecohydrological separation. This is therefore problematic because it tends to add weight to a single study more than it deserves given the high likelihood for its reported finding to be false (Ioannidis, 2005; Lakens & Etz, 2017).

Now we are not in any way trying to dismiss a challenge to an ecohydrological separation notion—and we are actively posing it as a null hypothesis to reject in our own work. We continue to make the call for sustained community effort in rejecting ecohydrological separation (Berry et al., 2017; McDonnell, 2014). And indeed, some recent work consolidates the view that ecohydrological separation poses many more open research questions than originally perceived (Bowling, Schulze, & Hall, 2016; Brantley et al., in press; Evaristo, McDonnell, & Clemens, 2017; Hervé-Fernández et al., 2016; Knighton, Saia, Morris, Archiblad, & Walter, 2017; McCutcheon, McNamara, Kohn, & Evans, 2016; Z. Q. Zhang, Evaristo, Li, Si, & McDonnell, 2017; Oerter & Bowen, 2017). But meta-analysis may provide a useful platform for generating large-scale evidence that would ultimately reject the ecohydrological separation hypothesis. Every primary study that putatively proves or disproves the hypothesis should be regarded as evidentiary support for or against the hypothesis. After all, mixed results in lines of research are increasingly likely when performing multiple studies that test the same hypothesis (Lakens & Etz, 2017).

4 | META-ANALYSIS AND PUBLICATION BIAS

One technique that could prove useful in future refutations to an earlier demonstration of support for a particular hypothesis would be a formal assessment of the risk of publication bias. Publication bias, or the file drawer problem (Rosenthal, 1979), is a problem for almost any synthesis work because scientific journals usually do not publish "negative results." This leads to missing studies and outcomes. In research fields outside the earth sciences, for example, there is evidence (e.g., Song, Eastwood, Gilbody, Duley, & Sutton, 2000) that studies are not only more likely to be published if the results are statistically significant ($p < 0.05$) but are also published sooner than studies with nonsignificant findings (Hopewell & Clarke, 2001). When a synthesis paper misses some studies due to publication bias, the review, whether a narrative review or meta-analysis, will be biased in favour of exaggerating a particular finding.

Thus, one way to challenge a prior demonstration of support for a particular hypothesis—for example, the ecohydrological separation hypothesis (Evaristo et al., 2015)—is via a formal risk assessment of publication bias. Following Evaristo and McDonnell (2017), we assessed the risks of publication bias in the xylem water isotopic data used by Evaristo et al. (2015). Results from classic *Fail-safe N* approach (Borenstein et al., 2010; Rosenthal, 1979) suggest that we would need 62,309 studies with a precipitation offset of zero to nullify ecohydrological separation. Stated differently, there would need to be 1,326 missing studies for every observed study for ecohydrological separation to be nullified. Given that the number of returned studies from a search of "xylem" and "isotope" in Scopus and ISI Web of Science databases was between 562 and 650 (accessed May 11, 2017), respectively, we rule out bias based on this approach. Of course, one might argue that the classic *Fail-safe N* approach is *purely statistical*. As such, one might extend this argument to assert that it cannot serve as basis for claiming the *scientific validity* of ecohydrological separation, at least within the precipitation offset framework (*sensu stricto* Evaristo et al., 2015). We do not suggest that ecohydrological separation is infallible; nothing in curiosity-driven science is. But we do suggest that refutations to a scientific finding be treated with cautious optimism. And if possible, refutations should be cast within the larger context of existing evidence using state-of-practice methods—using the statistics underlying a meta-analysis is one such method.

We recommend that future meta-analyses in hydrology follow state-of-practice guidelines. For example, QUOROM (*qu*ality *o*f *r*eporting *o*f *m*eta-analysis; Moher et al., 2000) and PRISMA (preferred reporting items for systematic reviews and meta-analyses; Liberati et al., 2009) involve an assessment of the risk of publication bias, or selective reporting within studies. Of the 87 papers that may be classified as meta-analysis in hydrology between 1990 and the early part of 2017 (Figure 1) none as far as we are aware (except for Evaristo and McDonnell, 2017) has made explicit assessment of publication bias and followed fully the PRISMA guidelines. This needs to change. Disciplines outside the earth sciences, particularly epidemiological and social sciences, are almost 20 years ahead of us in employing state-of-practice guidelines in meta-analytic reviews. We need to learn from these disciplines and adopt similar meta-analysis reporting guidelines.

5 | SUMMARY AND OUTLOOK

As researchers we are trained to perform literature reviews. But given the near-exponential growth in the number of hydrological studies published, the narrative manner with which we undertake traditional literature reviews leads invariably to subjectivity. We see a bright and important future for meta-analysis in aiding retrospective synthesis of published research whereby divergent (or mixed) results on the same research question are apparent. Future meta-analyses in hydrology can complement individual field studies (something we continue to strongly advocate for!) and narrative reviews. Meta-analysis, with appropriate assessment of publication bias, can place primary studies within a larger context of the research question of interest. Although hypothesis testing and exploratory research in basic field study in hydrological sciences can lead to new and important discoveries, it is important to acknowledge that such discoveries represent only a partial picture. Perhaps this incomplete picture will persist until large-scale hypothesis testing or exploratory research (alternatively, meta-analyses) are able to establish the generality of observations.

One hesitation for more widespread adoption of meta-analytic tools in hydrology may be the perception that its main utility—synthesis of results from arguably disparate studies—may somehow diminish the primacy of study setting, that is, that in hydrology *context is king* (Buttle, pers. comm. 2017). Such hesitation would be warranted if a meta-analyst asserts generalizability without a formal assessment of heterogeneity (i.e., dispersion) and publication bias. Thus, a compilation of studies only from one type of setting would result in a conclusion that is applicable only to the type of setting in question. On the contrary, a robust meta-analysis in hydrology—one that assesses heterogeneity and publication bias with statistical rigour—may provide a new and useful platform for addressing questions related to generalizability of results without unnecessarily diminishing the primacy of study setting, of import particularly in most water resource management programs. The future is bright for meta-analysis in hydrology, and there is much low-hanging fruit to be picked.

ACKNOWLEDGMENT

We thank Jim Buttle for valuable comments along the way.

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How to cite this article: Evaristo J, McDonnell JJ. A role for meta-analysis in hydrology. *Hydrological Processes*. 2017;1–4. https://doi.org/10.1002/hyp.11253